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Article

A Novel Gold Film-coated V-shape Dual-core Photonic Crystal Fiber Polarization Beam Splitter Covering the E+S+C+L+U Band

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Abstract: In this paper, a novel gold film-coated V-shape dual-core photonic crystal fiber (V-DC-PCF) polarization beam splitter (PBS) based on surface plasmon resonance effect is proposed. The coupling lengths of the X-polarization (X-pol) and Y-polarization (Y-pol) and the corresponding coupling length ratio of the proposed V-DC-PCF PBS without gold film and with gold film are compared. The fiber structure parameters and thickness of the gold film are optimized through investigating their effects on the coupling lengths and coupling length ratio. As the propagation length increases, the normalized output powers of the X-pol and Y-pol of the proposed V-DC-PCF PBS at the three wavelengths 1.610, 1.631, and 1.650 μm are demonstrated. The relationships between the extinction ratio (ER), insertion loss (IL) and wavelength for the three splitting lengths (SLs) 188, 185, and 182 μm are investigated. Finally, it is demonstrated that for the proposed V-DC-PCF PBS, the optimal SL is 188 μm , the ILs of the X-pol and Y-pol are less than 0.22 dB, and the splitting bandwidth (SB) can cover the E + S + C + L + U band. **The proposed V-DC-PCF PBS has the ultra-short SL, ultra-wide SB, and ultra-low IL, so it is expected to have important applications in the laser, sensing, and dense wavelength division multiplexing systems.**

Keywords: V-shape dual-core photonic crystal fiber; polarization beam splitter; surface plasmon resonance effect; extinction ratio; insertion loss

0. Introduction

Since the first photonic crystal fiber (PCF) was fabricated by Russell et al. in 1996 [1], the PCFs have been investigated extensively and applied in different optical fields, such as fiber laser, sensing, optical communication, and so on [2–8]. At present, the PCF-based optical devices, including polarization beam splitter (PBS), polarization filter, modulator, etc. have become the indispensable components in the all-fiber optical systems [9–14].

In recent years, the dual-core PCF (DC-PCF) PBS based on the coupled mode theory has been widely investigated [15–19]. In 2016, Zi et al. reported a simple DC-PCF PBS, whose splitting lengths

(SLs) are 249 and 506 μm and splitting bandwidths (SBs) are 17 and 12 nm at wavelengths 1.55 and 1.31 μm , respectively [20]. In the same year, Wang et al. proposed a liquid crystal-filled DC-PCF PBS, whose SL is 890.5 μm and SB covers the S + C + L band [21]. In 2017, He et al. designed an octagonal lattice DC-PCF PBS with the five elliptical air holes, whose SL is 105 μm and SB covers the S + C + L band [22]. In 2017, Wang et al. demonstrated a surface plasmon resonance (SPR) effect-based DC-PCF PBS filled with elliptical gold wire, whose SL is 1.079 mm and SB only covers the C band [23]. In 2018, Wang et al. achieved a short DC-PCF PBS with the liquid filled in the central and two elliptical air holes, whose SL is 78 μm and SB only covers the C band [24]. In 2019, Lou et al. investigated an ultrashort SPR effect-based DC-PCF PBS coated with gold film, whose SL is only 47.26 μm and SB cannot cover the C band [25]. From the previous works, the performances of the DC-PCF PBS can be obviously improved by introducing the elliptical air holes, changing the lattice arrangement of air holes, and selectively filling or coating the air holes with the liquid crystal, liquid, metal wire, and metal film.

Up to now, the fabrication technology of the PCFs with the circular air holes arranged in a hexagonal lattice has been developed more mature [26–32]. Many fabrication methods have been reported, including stack-and-draw, 3D printing, femtosecond laser drilling, etc [33–39]. In contrast, it is more difficult to fabricate the PCFs when the air holes are arranged in the rectangle and octagonal shapes or the elliptical air holes exist. Especially when selectively filling the metal wire or coating the metal film into the air holes of the PCFs, the difficulty of fabrication is further increased. Since Sazio et al. and Russell et al. firstly demonstrated the gold film-coated PCF in 2006 [40] and gold wire-filled PCF in 2008 [41], respectively, there are some reports on fabricating the gold film-coated and gold wire-filled PCFs by different methods [42–48]. At present, it is becoming a research hotspot to design and fabricate the gold film-coated or gold wire-filled DC-PCF PBS which has the hexagonal arrangement of circular air holes.

In this paper, we propose a novel gold film-coated V-shape DC-PCF (V-DC-PCF) PBS based on the SPR effect. We compare the coupling lengths (CLs) of the X-polarization (X-pol) and Y-polarization (Y-pol) and the coupling length ratio (CLR) when the proposed V-DC-PCF PBS is coated with and without gold film. At the three wavelengths 1.610, 1.631, and 1.650 μm , the normalized output powers of the X-pol and Y-pol of the V-DC-PCF PBS are demonstrated when the propagation length increases. For the three splitting lengths (SLs) 188, 185, and 182 μm , the extinction ratio (ER) and insertion loss (IL) of the proposed V-DC-PCF PBS are investigated. Finally, we obtain a V-DC-PCF PBS with good performances, whose optimal SLs is 188 μm , ILs of the X-pol and Y-pol are less than 0.22 dB, and SB can cover the E + S + C + L + U band.

1. Design of the V-DC-PCF PBS

The three-dimensional and cross-sectional structures of the proposed V-DC-PCF PBS are shown in Figure 1 (a) and 1 (b), respectively. From Figure 1 (a) and 1 (b), the substrate material is silica, the air holes are arranged in a hexagonal lattice, and the hole to hole pitch is Λ . The most central air hole with the diameter of d_1 is coated with the gold film, which has a thickness of t . **When the light energy is propagated inside the V-DC-PCF coated with gold film, the free electrons on the gold film surface interact with the incident light field, generating the SPR and exciting the surface plasmon polariton (SPP) mode on the gold film surface. At a specific wavelength, the core mode of the V-DC-PCF and SPP mode have the same propagation constant, so the mode coupling occurs due to the phase-matching condition.** The two air holes in the first layer along the X-direction of the V-DC-PCF are missing to form the two cores, which are labeled as the cores A and B, respectively. In the cladding region of the V-DC-PCF, there are two other sizes of air holes. The diameter of the smaller air holes on the left and right sides is d_2 , and the diameter of the larger air holes on the upper and lower sides is d_3 . In practice, such a V-DC-PCF can be fabricated with the stack-and-draw method, and the gold film can be selectively coated on the most central air hole by the chemical vapor deposition or magnetron sputtering technique [33,40,47].

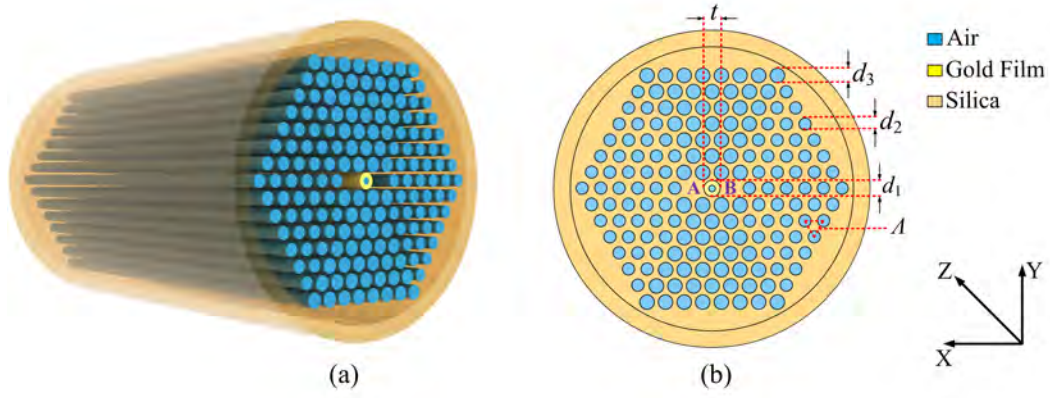


Figure 1. The three-dimensional (a) and cross-sectional (b) structures of the proposed V-DC-PCF PBS.

74 The material dispersion of the silica can be obtained by the Sellmeier equation as [49]

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1^2} + \frac{A_2\lambda^2}{\lambda^2 - B_2^2} + \frac{A_3\lambda^2}{\lambda^2 - B_3^2} \quad (1)$$

75 where λ is the wavelength of free space. The related parameters of the Sellmeier equation for the silica
76 material are shown in Table 1.

Table 1. The related parameters of the Sellmeier equation for the silica material.

A_1	A_2	A_3	B_1 (μm)	B_2 (μm)	B_3 (μm)
0.6961663	0.4079426	0.8974794	0.0684043	0.1162414	9.896161

The relative dielectric constant of the gold material can be described by the Drude-Lorentz model [50]

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega - j\gamma_D)} - \frac{\Delta\varepsilon \cdot \Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L\omega} \quad (2)$$

77 where ω is the angle frequency of the guided-wave, ε_∞ and $\Delta\varepsilon$ are the high frequency dielectric
78 constant and weighted coefficient, ω_D and γ_D are the plasma and damping frequencies, and Ω_L and
79 Γ_L are the frequency and bandwidth of the Lorentz oscillator, respectively. The specific parameters of
80 the Drude-Lorentz model for the gold material are shown in Table 2.

Table 2. The specific parameters of the Drude-Lorentz model for the gold material.

ε_∞	$\Delta\varepsilon$	$\omega_D/2\pi$ (THz)	$\gamma_D/2\pi$ (THz)	$\Omega_L/2\pi$ (THz)	$\Gamma_L/2\pi$ (THz)
5.9673	1.09	2113.6	15.92	650.07	104.86

The CLs in the X-pol and Y-pol directions of the V-DC-PCF PBS can be described as [51]

$$CL_X = \frac{\lambda}{2|(n_{even}^X - n_{odd}^X)|} \quad (3)$$

$$CL_Y = \frac{\lambda}{2|(n_{even}^Y - n_{odd}^Y)|} \quad (4)$$

81 where CL_X and CL_Y represent the CL of the X-pol and Y-pol, respectively, λ is the wavelength of the
82 initial incident light, and n_{even}^X , n_{odd}^X , n_{even}^Y , and n_{odd}^Y represent the effective refractive indices (ERIs)
83 of the even and odd modes in the X-pol and Y-pol, respectively.

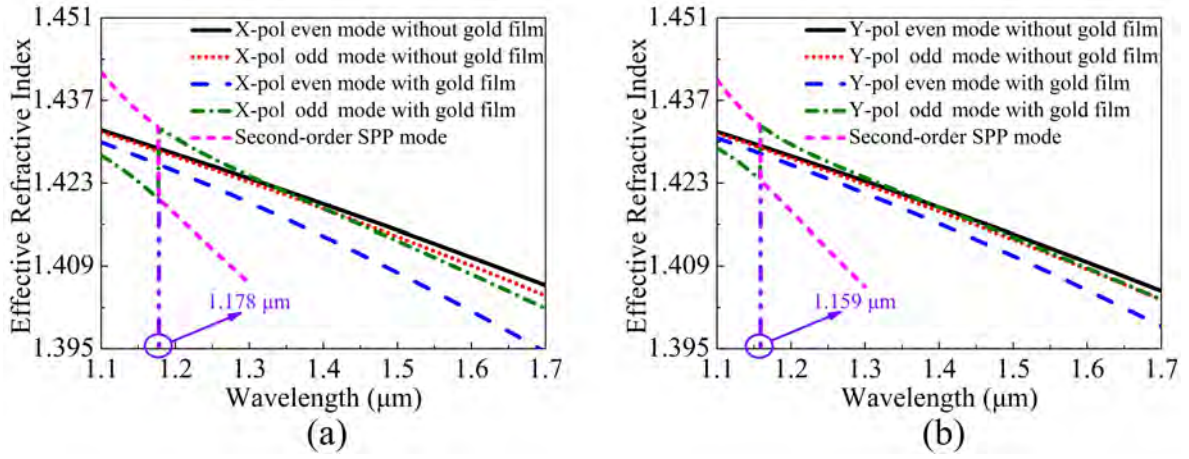


Figure 2. The ERIs of the (a) X-pol and (b) Y-pol even and odd modes and second-order SPP mode calculated as functions of wavelength when the V-DC-PCF is coated without gold film and with gold film, respectively.

The CLR can be calculated by [52]

$$CLR = \frac{CL_Y}{CL_X} \quad (5)$$

84 When the $CLR=2$ or $1/2$, the optimal SL can be obtained.

For the proposed V-DC-PCF PBS, we only need to consider the case that the initial incident light enters the core A or B since the geometric structure of the cores A and B are identical and symmetrical. In this work, when supposing that the initial incident light entering the core A, the output powers P_{out} of the X-pol and Y-pol in the core A can be described as [53]

$$P_{out,A}^{X,Y} = P_{in} \cos^2\left(\frac{\pi}{2} \frac{PL}{CL_{X,Y}}\right) \quad (6)$$

85 where P_{in} is the power of the initial incident light, and PL is the propagation length inside the
 86 V-DC-PCF PBS.

The ER of the core A, which is considered as a significant parameter for evaluating the splitting performance of the V-DC-PCF PBS, can be calculated by [54]

$$ER_A = 10 \log_{10} \frac{P_{out,A}^X}{P_{out,A}^Y} \quad (7)$$

The IL of the X-pol and Y-pol in the core A of the V-DC-PCF PBS can be described as [55]

$$IL_{X,Y} = -10 \log_{10} \frac{P_{out,A}^{X,Y}}{P_{in}} \quad (8)$$

87 2. Simulation Results and Discussion

88 The finite element method is used to investigate the propagation characteristics of the proposed
 89 V-DC-PCF [56,57]. The initial fiber structure parameters are set as following: $d_1=0.95 \mu\text{m}$, $d_2=1.20$
 90 μm , $d_3=1.40 \mu\text{m}$, $\Lambda=2.20 \mu\text{m}$, and $t=55 \text{ nm}$. In the simulation, the material coefficients including the
 91 refractive indices of the silica and air and the relative dielectric constant of the gold material are set
 92 after the simulation model is established. Then, a perfect matching layer (PML), whose thickness
 93 is $10 \mu\text{m}$ and refractive index is $n_{\text{silica}}+0.03$, is added to the outermost edge of the gold film-coated
 94 V-DC-PCF so as to absorb the radiation energy [58]. Moreover, the grid sizes of the silica, air holes, and
 95 PML are set as $\lambda/4$, and the grid size of the most central air hole coated with gold film is set as $\lambda/6$.

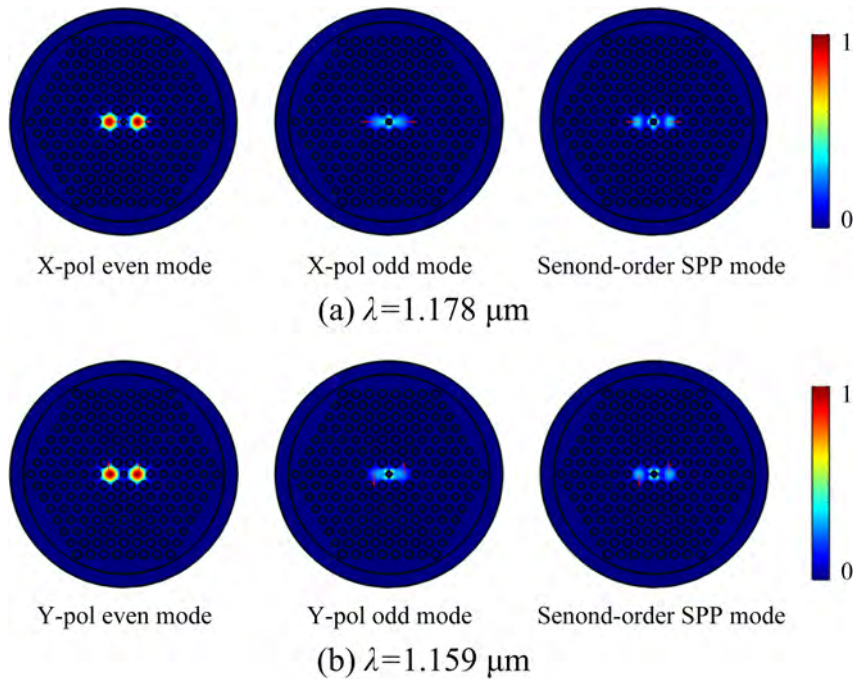


Figure 3. The mode field distributions of the (a) X-pol and (b) Y-pol even and odd modes and second-order SPP mode of the V-DC-PCF calculated at wavelengths 1.178 and 1.159 μm , respectively.

96 When the V-DC-PCF is coated without gold film and with gold film, the ERIs of the X-pol and
 97 Y-pol even and odd modes and second-order SPP mode are shown in Figure 2 (a) and 2 (b), respectively.
 98 It can be seen from Figure 2 (a) and 2 (b) that for the V-DC-PCF without gold film, the ERIs of the
 99 X-pol and Y-pol even and odd modes decrease approximately linearly with the increase of wavelength.
 100 Moreover, the ERIs of the X-pol and Y-pol odd modes decrease more obviously than that of the X-pol
 101 and Y-pol even modes at the longer wavelength side, but the differences between the X-pol or Y-pol
 102 even and odd modes are very small. According to Eqs. (3) and (4), we can infer that the CL_X and
 103 CL_Y will also change in the approximately linear trend and have large values. In contrast, when
 104 the V-DC-PCF is coated with gold film, the ERIs of the X-pol and Y-pol even modes still decrease
 105 approximately linearly as the wavelength increases. However, there are two cross points between
 106 the ERIs of the X-pol and Y-pol odd modes and second-order SPP mode at wavelengths 1.178 and
 107 1.159 μm , respectively, where the phase-matching condition is satisfied. According to the coupled
 108 mode theory, the X-pol and Y-pol odd modes occur to couple with the second-order SPP mode at
 109 wavelengths 1.178 and 1.159 μm , respectively. In addition, it can be seen from Figure 2 (a) and 2 (b)
 110 that before the phase-matching wavelengths, the ERIs of the X-pol and Y-pol odd modes decrease
 111 rapidly, along with a relatively small and stable slope. Hence, the differences between the ERIs of the
 112 X-pol and Y-pol even and odd modes increase rapidly with the increase of wavelength. The ERIs of
 113 the X-pol and Y-pol odd modes increase significantly at wavelengths 1.178 and 1.159 μm , respectively,
 114 and there are maximum differences between the ERIs of the X-pol and Y-pol even and odd modes.
 115 Thus, the CL_X and CL_Y will have significant changes at wavelengths 1.178 and 1.159 μm , respectively.
 116 But after the phase-matching wavelengths, the ERIs of the X-pol and Y-pol odd modes first decrease
 117 rapidly and then maintain a relatively stable slope. Finally, the relatively stable slope of the ERIs of the
 118 X-pol and Y-pol odd modes will be smaller than that of the ERIs of the X-pol and Y-pol even modes as
 119 the wavelength increases. Therefore, the differences between the ERIs of the X-pol and Y-pol even and
 120 odd modes first decrease and then increase as the wavelength increases. Figure 3 (a) and 3 (b) show
 121 the mode field distributions of the X-pol and Y-pol even and odd modes and second-order SPP mode
 122 calculated at wavelengths 1.178 and 1.159 μm , respectively. From Figure 3 (a) and 3 (b), the mode field
 123 distributions of the X-pol and Y-pol even modes have no change at wavelengths 1.178 and 1.159 μm ,

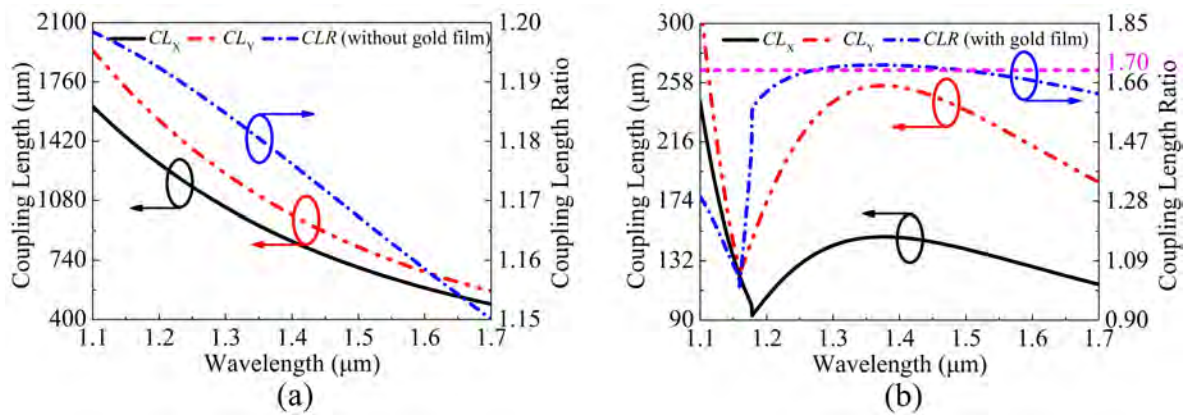


Figure 4. The CL_X , CL_Y , and CLR as functions of the wavelength when the V-DC-PCF is coated (a) without gold film and (b) with gold film.

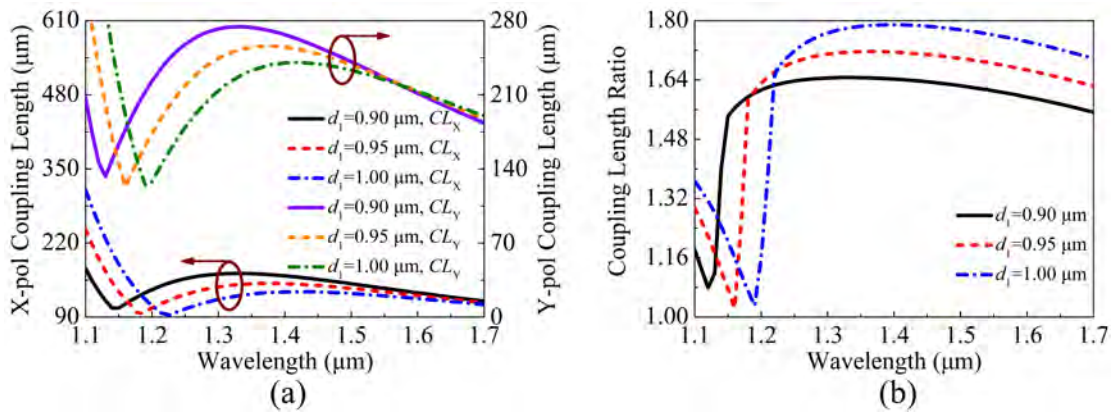


Figure 5. The variations of the (a) CL_X , CL_Y , and (b) CLR of the proposed V-DC-PCF PBS for different d_1 .

124 respectively. But the mode field energies of the X-pol and Y-pol odd modes and second-order SPP
 125 mode occur to transfer at the two wavelengths. It further confirms the previous conclusion that only
 126 the X-pol and Y-pol odd modes and second-order SPP mode occur to couple at the phase-matching
 127 wavelengths.

128 The relationships between the CL_X , CL_Y , and CLR and wavelength are shown in Figure 4 (a)
 129 and 4 (b), respectively, when the V-DC-PCF is coated without gold film and with gold film. It can
 130 be seen from Figure 4 (a) that when the V-DC-PCF is coated without gold film, the CL_X and CL_Y
 131 decrease gradually, and the corresponding CLR also decreases in an approximately linear trend as the
 132 wavelength increases. According to Eqs. (3) and (4) and the above analysis, when the V-DC-PCF is
 133 coated with gold film, the CL_X and CL_Y decrease rapidly before the phase-matching wavelengths, and
 134 occur to change significantly at wavelengths 1.178 and 1.159 μm , respectively, as shown in Figure 4 (b).
 135 After the phase-matching wavelengths, the CL_X and CL_Y increase first and then decrease. At this time,
 136 according to Eq. (5), the CLR decreases rapidly before wavelength 1.159 μm , has a significant change
 137 between wavelength 1.159 and 1.178 μm , and increases first and then decreases after wavelength 1.178
 138 μm . However, after wavelength 1.178 μm , the overall change of the CLR is relatively flat. In addition,
 139 the CLR has the two intersections, where the CLR is equal to 1.7. By comparing Figure 4 (a) and 4 (b),
 140 the maximum CL for the V-DC-PCF with gold film is smaller than the minimum CL for the V-DC-PCF
 141 without gold film, which has a direct effect on the SL of the V-DC-PCF PBS. From the above analysis, it
 142 is possible to achieve a PBS with the shorter SL and larger SB by using a V-DC-PCF with gold film.

143 The structure parameters of the proposed V-DC-PCF PBS with gold film need to be optimized
 144 to satisfy the condition of $CLR = 2$, which corresponds to the optimal SL . When the fiber structure

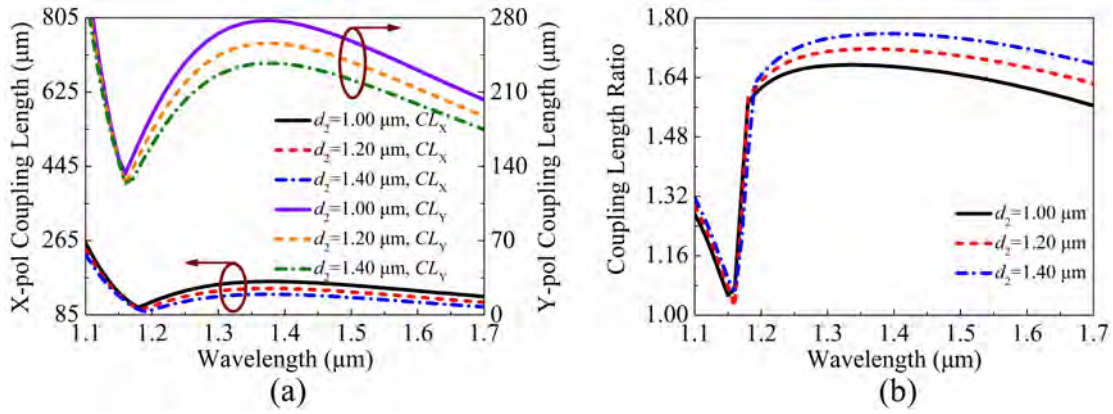


Figure 6. The variations of the (a) CL_X, CL_Y , and (b) CLR of the proposed V-DC-PCF PBS for different d_2 .

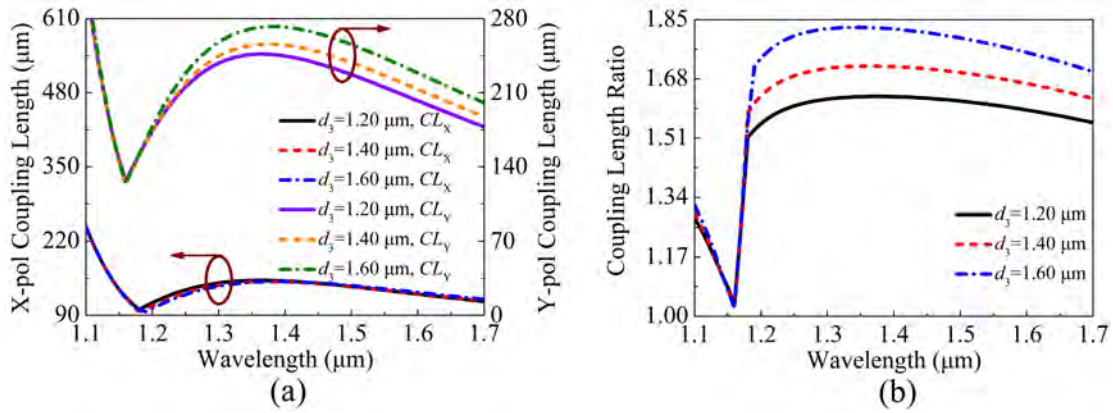


Figure 7. The variations of the (a) CL_X, CL_Y , and (b) CLR of the proposed V-DC-PCF PBS for different d_3 .

145 parameters, including d_1, d_2, d_3, Λ , and t are changed, respectively, the ERIs of the X-pol and Y-pol
 146 even and odd modes will occur to change in different degrees, which can also cause the changes of
 147 the CL_X, CL_Y , and CLR . The variations of the CL_X, CL_Y , and CLR of the proposed V-DC-PCF PBS are
 148 shown in Figure 5 (a) and 5 (b) when d_1 is chosen as 0.90, 0.95, and 1.00 μm , respectively. It can be seen
 149 from Figure 5 (a) that the CL_X and CL_Y decrease as d_1 increases at the short wavelength side. At the
 150 long wavelength side, as d_1 increases, the CL_X still decreases slightly, while the CL_Y shows a slightly
 151 increased trend. The CLR gradually increases as d_1 increases, and the phase-matching wavelength
 152 occurs to red-shift, as shown in Figure 5 (b).

153 The variations of the CL_X, CL_Y , and CLR of the proposed V-DC-PCF PBS are shown in Figure 6
 154 (a) and 6 (b) when d_2 is chosen as 1.00, 1.20, and 1.40 μm , respectively. It can be seen from Figure 6 (a)
 155 and 6 (b) that as d_2 increases, the CL_X and CL_Y gradually decrease while the CLR shows an increased
 156 trend. In addition, the change of the phase-matching wavelength is not obvious, and only a slight
 157 red-shift occurs as d_2 increases.

158 When d_3 is chosen as 1.20, 1.40, and 1.60 μm , respectively, the variations of the CL_X, CL_Y , and
 159 CLR of the proposed V-DC-PCF PBS are shown in Figure 7 (a) and 7 (b). From Figure 7 (a), as d_3
 160 increases, the CL_X decreases slightly at the short wavelength side and remains nearly unchanged
 161 at the long wavelength side. In comparison, the CL_Y gradually increases as d_3 increases, and the
 162 corresponding change amplitude at the long wavelength side is larger than that at the short wavelength
 163 side. As shown in Figure 7 (b), as d_3 increases, the CLR gradually increases, and the position of the
 164 phase-matching wavelength remains unchanged.

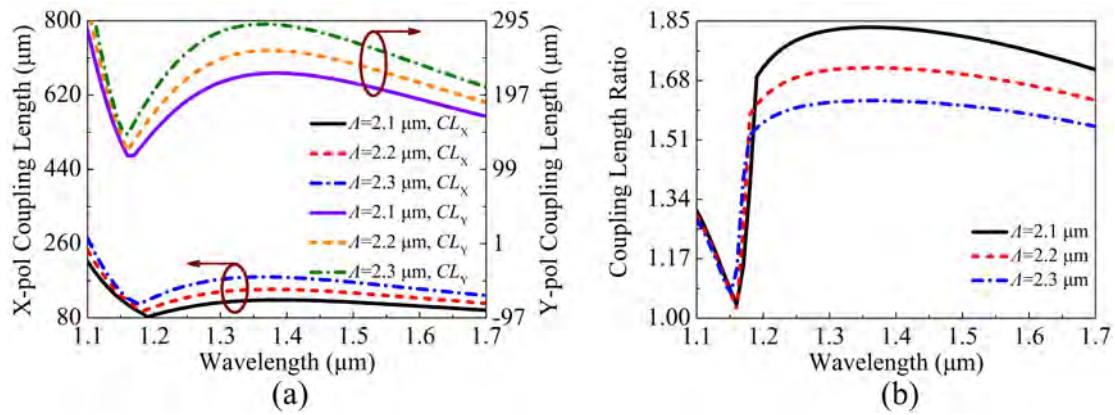


Figure 8. The variations of the (a) CL_X , CL_Y , and (b) CLR of the proposed V-DC-PCF PBS for different Λ .

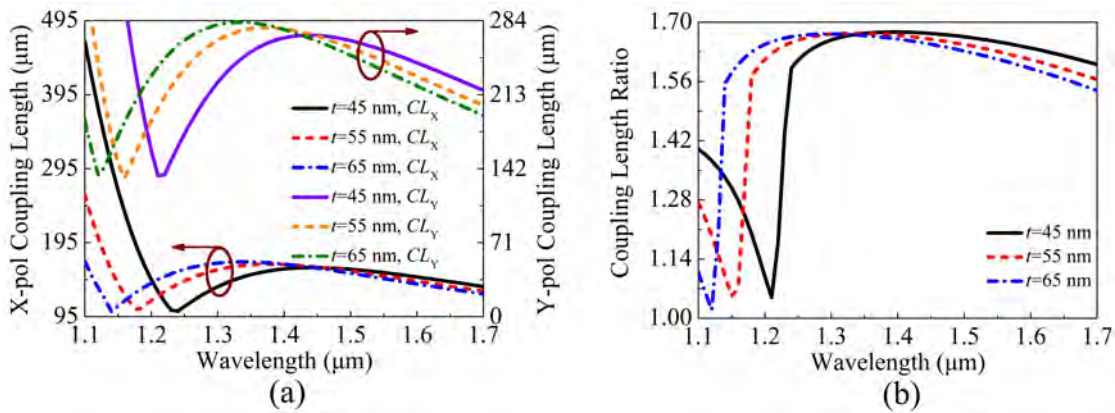


Figure 9. The variations of the (a) CL_X , CL_Y , and (b) CLR of the proposed V-DC-PCF PBS for different t .

165 The variations of the CL_X , CL_Y and CLR of the proposed V-DC-PCF PBS are shown in Figure 8 (a)
 166 and 8 (b) when Λ is chosen as 2.1, 2.2, and 2.3 μm , respectively. Figure 8 (a) and 8 (b), as Λ increases,
 167 the CL_X and CL_Y gradually increase, but the CLR shows a decreasing trend. In addition, the change of
 168 the phase-matching wavelength is not obvious, along with a small shift towards the short wavelength
 169 side. By comparing the results shown in Figure 5 (b), 6 (b), 7 (b), and 8 (b), it is found that the change
 170 of Λ has the most remarkable influence on the CLR .

171 Figure 9 (a) and 9 (b) show the variations of the CL_X , CL_Y , and CLR of the proposed V-DC-PCF
 172 PBS when t is chosen as 45, 55, and 65 nm, respectively. It can be seen from Figure 9 (a) that as t
 173 increases, the CL_X and CL_Y increase at the short wavelength side and decrease at the long wavelength
 174 side. It can be seen from Figure 9 (b) that as t increases, the CLR increases at the short wavelength
 175 side and decreases at the long wavelength side, and the position of the phase-matching wavelength
 176 gradually shifts towards the short wavelength side.

177 Based on the above analysis, the influence rule of the structure parameters of the proposed
 178 V-DC-PCF PBS on the CL_X , CL_Y , and CLR can be clearly known. Thus, the empirical steps for
 179 designing such a V-DC-PCF PBS can be summarized as following. First, by together adjusting d_1
 180 and t , the phase-matching condition can be achieved at the shorter wavelength, and the value of
 181 the CLR is close to 2. At this time, a relatively flat CLR curve can be obtained in the desired band.
 182 Second, by together adjusting d_2 , d_3 , and Λ , the CLR curve with the relatively flat profile and the
 183 value of 2 can be obtained when the phase-matching wavelength does not change obviously. Thus,
 184 the optimized structure parameters of the proposed V-DC-PCF PBS are chosen as follows: $d_1=1.00$
 185 μm , $d_2=1.41 \mu\text{m}$, $d_3=1.50 \mu\text{m}$, $\Lambda=2.10 \mu\text{m}$, and $t=46.5 \text{ nm}$. At this time, the variations of the optimal

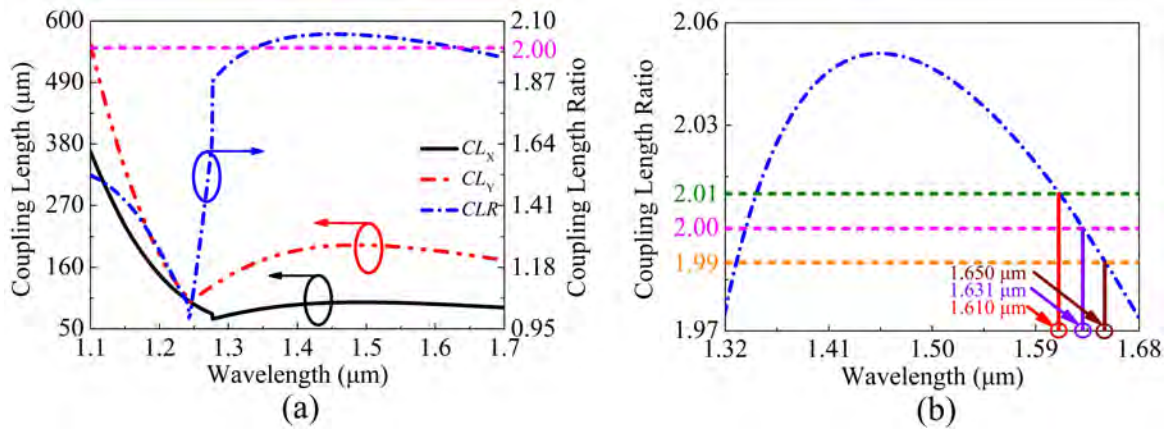


Figure 10. The optimal CL_X , CL_Y , and CLR of the proposed V-DC-PCF PBS, and (b) the zoomed flat region of the CLR .

186 CL_X , CL_Y , and CLR of the proposed V-DC-PCF PBS and the corresponding zoomed flat region of the
 187 CLR are shown in Figure 10 (a) and 10 (b), respectively. From Figure 10 (a), the CL_X and CL_Y have
 188 significant changes at the phase-matching wavelengths 1.277 and 1.243 μm , respectively. Moreover,
 189 the CLR is approximately equal to 2 in a wide wavelength range of above 1.277 μm . From Figure 10
 190 (b), the value of the CLR changes from 1.974 to 2.051 in the wavelength range from 1.32 to 1.68 μm ,
 191 and the maximum difference of the CLR between wavelength 1.32 and 1.68 μm is 0.077. In addition,
 192 the values of the CLR at wavelengths 1.610, 1.631, and 1.650 μm are 2.01, 2.00, and 1.99, respectively,
 193 which are approximately equal to 2. It is worth noting that although the value of the CLR is also equal
 194 to 1.99, 2.00, and 2.01 at other three shorter wavelengths, but the corresponding slope variation of the
 195 CLR is larger, which will affect the overall bandwidth to a great extent.

196 In the following, the relationships between the output powers P_{out} of the X-pol and Y-pol of
 197 the proposed V-DC-PCF PBS and PL at the three wavelengths 1.610, 1.631, and 1.650 μm are shown
 198 in Figure 11 (a), 11 (b), and 11 (c), respectively. From Figure 11 (a), 11 (b), and 11 (c), P_{out} of the
 199 X-pol reaches the maximum values when the PL is located at 188, 185, and 182 μm , respectively. In
 200 contrast, the corresponding P_{out} of the Y-pol reaches 0 when the PL is located at 188, 185, and 182 μm ,
 201 respectively. This phenomenon indicates that the X-pol light only exists in the core A while the Y-pol
 202 light only exists in the core B at the three PL s. Therefore, the SL of the proposed V-DC-PCF PBS may
 203 be 182, 185, or 188 μm . Moreover, another notable phenomenon is that the total P_{out} decreases slightly
 204 as the PL increases. This is mainly because a fraction of the energy always propagates on the surface
 205 of the gold film, leading to the increase of the ohmic loss.

206 When the SL is equal to 182, 185, and 188 μm , respectively, the relationships between the ER s in
 207 the core A of the proposed V-DC-PCF PBS and wavelength are shown in Figure 12. It can be seen from
 208 Figure 12 that for the SL s of 182 and 185 μm , the ER s are less than 20 dB in some wavelength ranges.
 209 In contrast, when SL is equal to 188 μm , the ER is always larger than 20 dB in a wide wavelength range
 210 from 1.359 to 1.677 μm . Figure 13 shows the relationships between the IL s of the X-pol and Y-pol in
 211 the core A of the proposed V-DC-PCF PBS and wavelength when the SL is equal to 182, 185, and 188
 212 μm , respectively. From Figure 13, for the SL s of 182, 185, and 188 μm , the maximum IL of the X-pol
 213 and Y-pol is 0.22 dB in the wavelength range of 1.359 to 1.677 μm . Such a small IL can meet the actual
 214 application requirements. **Because the proposed V-DC-PCF PBS has the ultra-short SL , the bending**
 215 **loss can be neglected.** Therefore, we can draw a conclusion that for the proposed V-DC-PCF PBS, the
 216 optimal SL is 188 μm , the SB covers the entire E + S + C + L + U band, and the IL s of the X-pol and
 217 Y-pol are less than 0.22 dB.

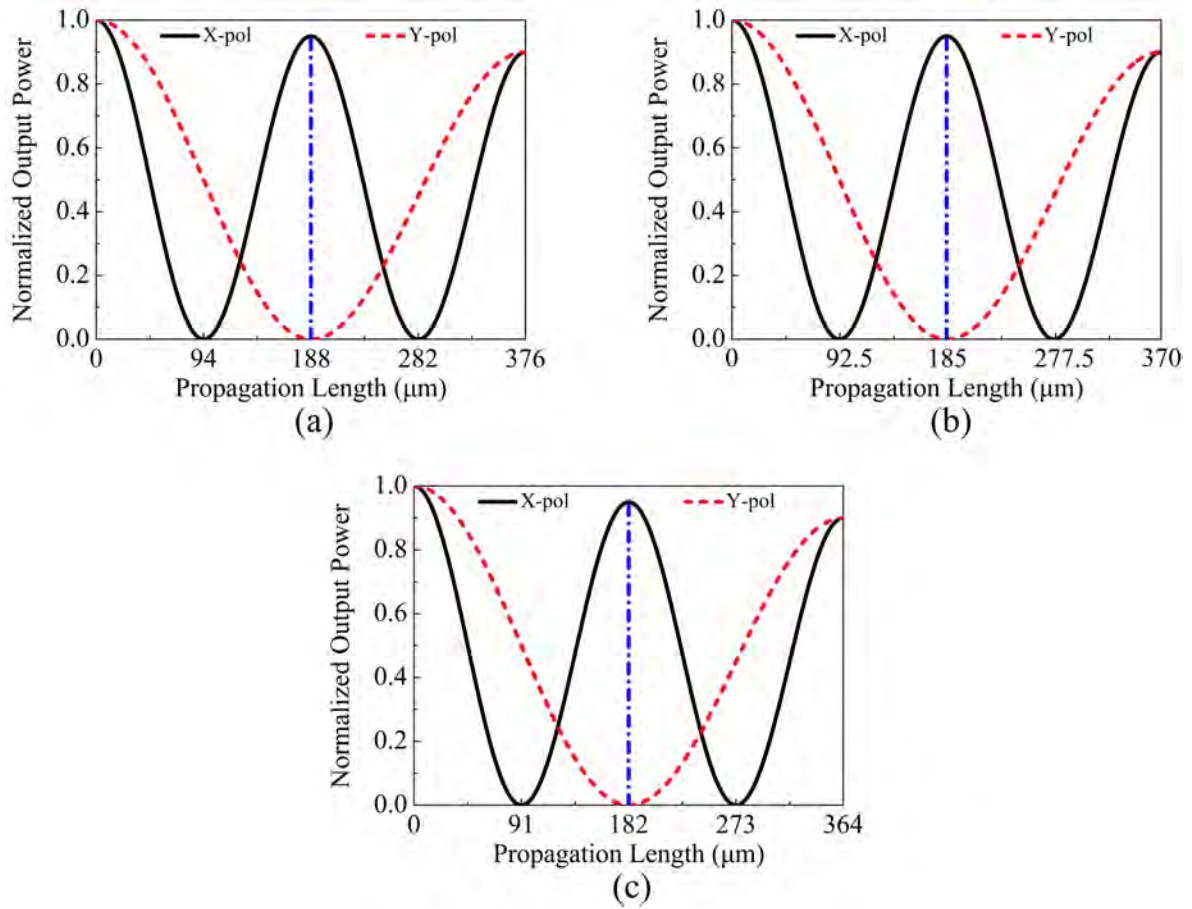


Figure 11. The relationships between the output powers P_{out} of the X and Y-pol of the proposed V-DC-PCF PBS and PL at the three wavelengths (a) 1.610, (b) 1.631, and (c) 1.650 μm , respectively.

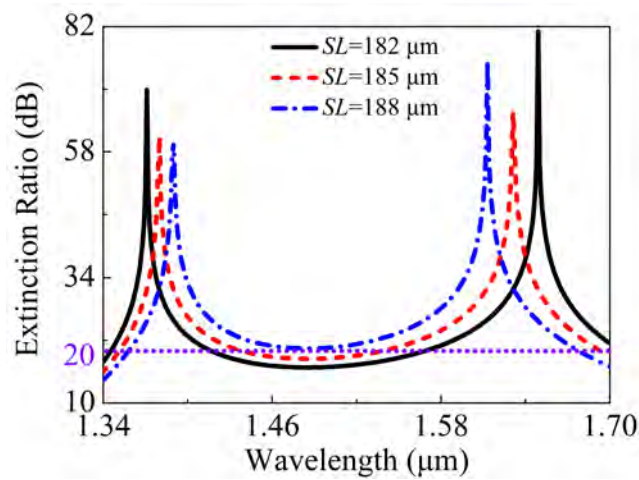


Figure 12. The ERs in the core A of the proposed V-DC-PCF PBS as functions of the wavelength for different SL .

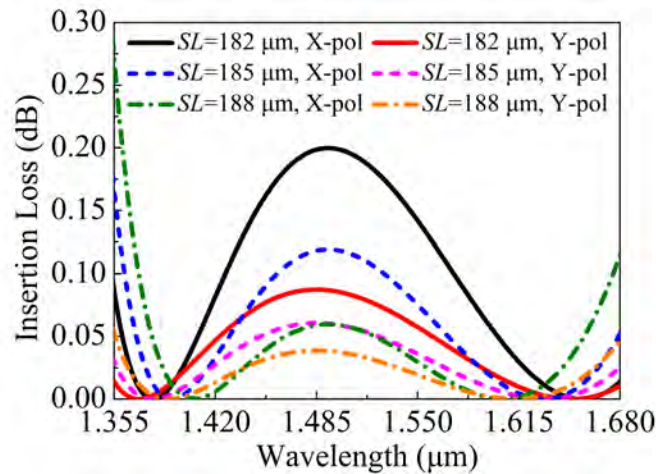


Figure 13. The *ILs* of the X-pol and Y-pol in the core A of the proposed V-DC-PCF PBS as functions of the wavelength for different *SL*.

Table 3. Comparisons between the proposed V-DC-PCF PBS and reported SPR-based DC-PCF PBS.

Ref.	DC-PCF structure	Gold film or wire	SB	SL	Max <i>IL</i>
[12]	Square lattice with circular air holes	Gold wire	O + E + S + C + L + U band	4.036 mm	0.8 dB
[13]	Hexagonal lattice with elliptical air holes	Gold wire	S + C + L + U band	254.6 μm	N/A
[14]	Hexagonal lattice with circular air holes	Gold wire	O and C bands	830 μm	N/A
[15]	D-shape hexagonal lattice with circular air holes	Gold film	C band	0.782 mm	1.5 dB
[16]	Hexagonal lattice with circular air holes	Gold wire	S + C + L + U band	577.5 μm	N/A
[17]	Rectangle lattice with circular air holes	Two gold wires	E + C band	1 mm	N/A
[18]	Hexagonal lattice with circular air holes	Gold film	S + C + L band	5.112 mm	N/A
[24]	Hexagonal lattice with circular air holes	Elliptical gold wire	C band	1.079 mm	N/A
[25]	Square lattice with circular air holes	Gold film	S + C + L band	47.26 μm	N/A
This work	Hexagonal lattice with circular air holes	Gold film	E + S + C + L + U band	188 μm	<0.22 dB

218 The comparisons between the proposed V-DC-PCF PBS and reported SPR-based DC-PCF PBS are
 219 shown in Table 3. From Table 3, only the *SB* of the SPR-based DC-PCF PBS reported in Ref [12] is larger
 220 than that of the proposed V-DC-PCF PBS. However, in Ref [12], the *SL* and minimum *IL* are 4.036 mm
 221 and 0.8 dB, respectively, while they are only 188 μm and 0.22 dB in this work. Moreover, the air holes
 222 of the DC-PCF PBS reported in Ref [12] are arranged in a square lattice, so it is difficult to fabricate. In
 223 addition, only the *SL* of the SPR-based DC-PCF PBS reported in Ref [25] is shorter than that of this
 224 work. However, in Ref [25], the *SB*, which covers the S + C + L band, is much narrower than that of
 225 this work, and the *IL* is not given. Moreover, the air holes of square lattice of the DC-PCF PBS reported
 226 in Ref [25] also increase the difficulty of fabrication. In summary, the proposed V-DC-PCF PBS has the
 227 good comprehensive performances.

228 The *ERs* in the core A and *ILs* of the X-pol and Y-pol in the core A of the proposed V-DC-PCF
 229 PBS are shown in Figure 14 (a) and 14 (b) when *t* changes $\pm 1\%$. From Figure 14 (a), the wavelength
 230 range of the *ER* larger than 20 dB changes slightly, which indicates that the proposed V-DC-PCF PBS

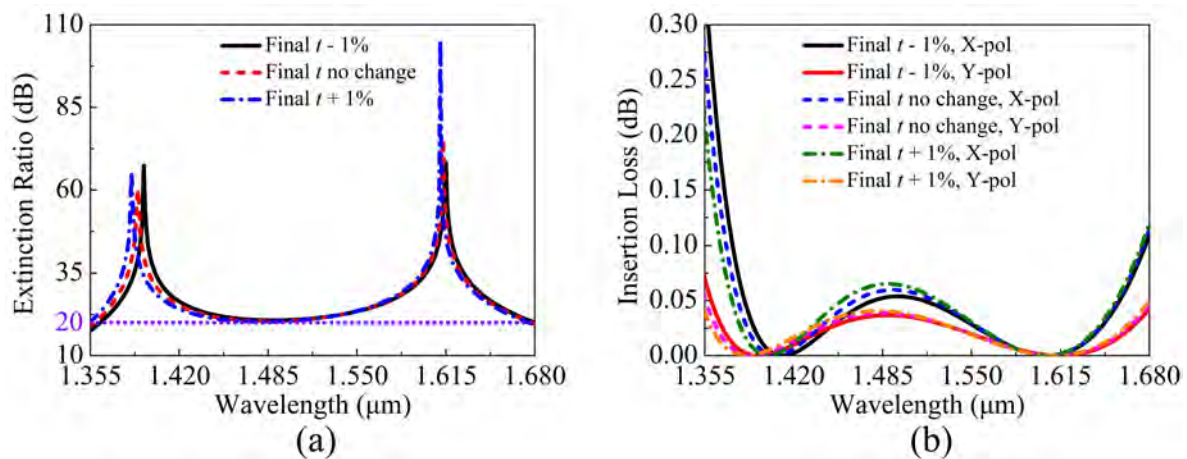


Figure 14. (a) ERs in the core A and (b) ILs of the X-pol and Y-pol in the core A of the proposed V-DC-PCF PBS as functions of wavelength when t has the distortion of $\pm 1\%$.

231 still has a wide SB. From Figure 14 (b), the ILs of the X-pol and Y-pol are always less than 0.22 dB in
 232 each SB. Thus, t has good error-tolerant rate in the actual coating process.

233 3. Conclusion

234 In summary, a novel gold film-coated V-DC-PCF PBS based on the SPR effect is proposed. The
 235 CL_X , CL_Y , and CLR of the proposed V-DC-PCF PBS coated without gold film and with gold film are
 236 investigated. The empirical steps for designing such a V-DC-PCF PBS are summarized by analyzing
 237 the effects of the fiber structure parameters on the CL_X , CL_Y , and CLR . The CLR of 2 can be obtained
 238 at the three wavelengths 1.610, 1.631, and 1.650 μm. When the SL s are equal to 188, 185, and 182 μm,
 239 the relationships between the ER, IL and wavelength are investigated, respectively. The proposed
 240 V-DC-PCF PBS has the good comprehensive performances, including the SL of 188 μm, IL of less than
 241 0.22 dB, and SB of covering the E + S + C + L + U band. It is believed that the proposed V-DC-PCF
 242 PBS can find important applications in the laser, sensing, and dense wavelength division multiplexing
 243 systems.

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